

# Natural Characteristics Research of MW Wind Turbine Tower

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## Abstract

The natural characteristics calculation modal of the first step bending and torsional vibration was established based on Rayleigh method for MW wind turbine tower. The influence of the diameter, thickness, taper angle, nacelle and rotor mass, offset of mass on the inherent characteristic of tower was studied. Finite element method (FEM) was also used to calculate the inherent characteristic of tower and the FEM results showed good agreement with Rayleigh method results. Finally, the influence of dimension and position of the door on the basic frequency was investigated by means of FEM.

## Keywords

*Mw Wind Turbine; Tower; Natural Characteristics; Rayleigh Method; Fem*

## Introduction

MW wind turbine tower is used to support the weight of mechanical and electrical components and bear the force due to the wind. It is necessary to analyze the inherent characteristic of tower to avoid the resonance area because of the periodicity excitation force from the rotation of rotor.

At present, there are several methods to study the inherent characteristic of tower, such as analytical method (analytical dynamics and multi-body dynamics), FEM and experiment method. Natural characteristics of the first step bending vibration has been solved for small-scale wind turbine tower with Rayleigh method, though the results showed good agreement with FEM and experiment, the natural characteristics of torsional vibration was neglected and the model was simplified. The low order natural frequency of MW wind turbine tower was computed and the influence of nacelle mass on tower natural characteristics was studied with FEM, but there was no discussion on the influence of mass central position and other factors. The influence of the diameter,

thickness, top mass on the tower natural frequency was researched based on FEM, however, the analysis project was too limited to describe the relationships accurately. The tower natural frequency was obtained from experiment, so the FEM result was validated. In this paper, Rayleigh method as well as FEM was used to study the natural characteristics of tower based on previous research work, and the analysis conclusion will be favourable to the design of tower.

## Natural Characteristics Study of Tower with Rayleigh Method

The frequency of bending and torsional vibration has been greatly considered for the tower natural characteristics research, and the key factor of the structural response is the lower frequency. Therefore, only the first step natural frequency of bending and torsional vibration was taken into account to research the tower natural characteristics under the aid of Rayleigh method.

## Analyzing Model for Tower

The MW wind turbine tower is usually designed as a taper cylinder structure, in which the top is joined to the yaw system, while the bottom is fixed with the foundation. The tower consists of several short taper cylinders with flange, whose thickness varies with the height, and there is a door serving as inlet at the bottom. The tower approximately regarded as a non-uniform section beam has lumped mass (replaced by  $M$ ), as well as the moment of inertia (replaced by  $J_{NB}$ ) at one end and is fixed at the other end.

The 3-section tower is divided into three different uniform sections beams, the stiffness can be calculated based on equivalent stiffness method respectively, and the eccentricity between top centroid and centre of beam can be regarded as variable  $\Delta l$ , which is shown in Figure1.  $M$  is the whole mass of all the structures

except tower and  $J_{NB}$  is the moment of inertia of nacelle and rotor.

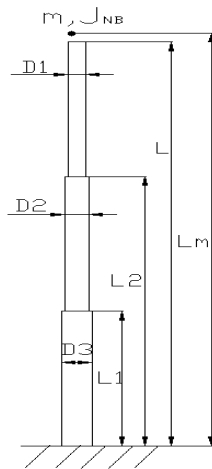


FIG.1 ANALYZING MODAL FOR TOWER

### Mechanical Modal for Tower Based on Rayleigh Method

Rayleigh method, an appropriate method to obtain the natural frequency based on the law of the conservation of mechanical energy, is used to calculate the approximate solution of natural frequency for tower in this paper. Firstly, vibration function matching boundary condition should be given to seek for the natural frequency of bending vibration. The vibration function  $C$  is supposed as the calculation function in this paper, and the static deflection can be calculated with function:  $Y_x = \delta x^3 L^{-3}$ , where  $x$  is height,  $Y_x$  is the static deflection corresponding to  $x$ , and  $\delta$  is the amplitude of bending. The tower has three sections, in which the stiffness and the mass of unit length are different from each other. Therefore the maximal bending potential energy of beams is calculated as:

$$U_{\max} = \frac{1}{2} \left[ \int_0^{L_1} EI_1 \left( \frac{d^2 Y}{dx^2} \right)^2 dx + \int_{L_1}^{L_2} EI_2 \left( \frac{d^2 Y}{dx^2} \right)^2 dx + \int_{L_2}^L EI_3 \left( \frac{d^2 Y}{dx^2} \right)^2 dx \right] \quad (1)$$

Where  $E$  is elastic modulus,  $I_1, I_2, I_3$  are the moment inertia of cross section for each beam, respectively.

And the maximal bending kinetic energy of the beams is calculated as:

$$T_{\max} = \frac{\omega_b^2}{2} \left( \int_0^{L_1} \rho A_1 Y_{(x)}^2 dx + \int_{L_1}^{L_2} \rho A_2 Y_{(x)}^2 dx + \int_{L_2}^L \rho A_3 Y_{(x)}^2 dx + m Y_{(L_m)}^2 \right) \quad (2)$$

Where  $\rho$  is density of material,  $A_1, A_2, A_3$  are the area of cross section for each beam, respectively. According to the law of the conservation of energy:  $T_{\max} = U_{\max}$ , the

natural frequency of bending vibration can be calculated as following:

$$\omega_b = \sqrt{\frac{\int_0^{L_1} EI_1 \left( \frac{d^2 Y}{dx^2} \right)^2 dx + \int_{L_1}^{L_2} EI_2 \left( \frac{d^2 Y}{dx^2} \right)^2 dx + \int_{L_2}^L EI_3 \left( \frac{d^2 Y}{dx^2} \right)^2 dx}{\int_0^{L_1} \rho A_1 Y_{(x)}^2 dx + \int_{L_1}^{L_2} \rho A_2 Y_{(x)}^2 dx + \int_{L_2}^L \rho A_3 Y_{(x)}^2 dx + m Y_{(L_m)}^2}} \quad (3)$$

The solution to the first step torsional frequency is the same as the bending. The static torsion deflection can be calculated by means of the same method:

$\theta_x = \epsilon x^2 L^{-2}$ , where  $\epsilon$  is the amplitude of torsion. Then the natural frequency of torsional vibration can be calculated as follows:

$$\omega_t = \sqrt{\frac{\int_0^{L_1} GJ_1 \left( \frac{d\theta}{dx} \right)^2 dx + \int_{L_1}^{L_2} GJ_2 \left( \frac{d\theta}{dx} \right)^2 dx + \int_{L_2}^L GJ_3 \left( \frac{d\theta}{dx} \right)^2 dx}{\int_0^{L_1} I_{P1} \theta_{(x)}^2 dx + \int_{L_1}^{L_2} I_{P2} \theta_{(x)}^2 dx + \int_{L_2}^L I_{P3} \theta_{(x)}^2 dx + (J_{NB} + m(\Delta l)^2) \theta_{(L_m)}^2}} \quad (4)$$

Where  $GJ_1, GJ_2, GJ_3$  are the stiffness of torsion for each beam, while  $I_{P1}, I_{P2}, I_{P3}$  are the unit length mass moment of inertia for each beam.

### Natural Characteristics Research on Tower

It is important for designers to make sure that the tower natural frequency is beyond the frequency range of excitation force. Engineering experiences indicate

that the resonance frequency is usually close to the natural frequency of bending and torsional vibration of tower. The two frequencies are influenced by these factors such as diameter, thickness, taper angle, centroid mass and eccentricity and so on. The in-depth research on the tower natural character has been carried out with the mechanical modal established in chapter 2.2, and the objective is some MW wind turbine tower. The parameters used for the calculated modal are listed as following: the height is 67 m; the outer diameter in the top and the bottom is 4 m and 2.65 m, respectively; the maximal and minimum thickness is 30 mm and 12 mm, respectively; the nacelle mass is 100 ton, the moment of inertia is  $4e5 \text{ kg}\cdot\text{m}^2$ , and the eccentricity is 0.5 m. All other parameters are supposed constant when the influence of one of them on the natural frequency is investigated.

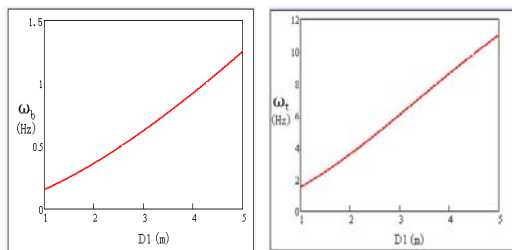


FIG.2 INFLUENCE OF THE OUTER DIAMETER IN THE TOP D1 ON THE NATURAL FREQUENCY  $\Omega_b$  AND  $\Omega_t$

The influence of the outer diameter in the top D1 on the natural frequencies of bending ( $\omega_b$ ) and torsional ( $\omega_t$ ) vibration was shown in Figure 2, and the natural frequencies  $\omega_b$  and  $\omega_t$  rises with the increase of variable D1.

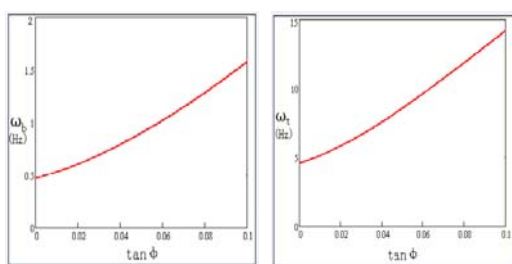


FIG.3 INFLUENCE OF T TAPER ANGLE  $\phi$  ON THE BASIC FREQUENCY  $\omega_b$  AND  $\omega_t$

Generally, the diameter of tower in the top is determined by the dimension of yaw system, so D1 can't be changed optionally. However, the natural frequencies of  $\omega_b$  and  $\omega_t$  can be modified by the taper angle  $\phi$ . The taper angle  $\phi$  can be altered by D2 and D3, both of which are the outer diameter of middle and bottom beam. The relationship among  $\tan \phi$  and  $\omega_b$  and  $\omega_t$  is presented in figure 3, in which the natural

frequencies  $\omega_b$  and  $\omega_t$  increase with the rise of taper angle  $\phi$ .

Thickness is another important factor influencing the tower natural frequency. The influence of variable  $t_1$ ,  $t_2$ ,  $t_3$  on the basic frequencies  $\omega_b$  and  $\omega_t$  have been illustrated in Figure 4, where  $t_1$ ,  $t_2$ ,  $t_3$  separately represent the thickness of the top, middle and bottom. The figures show that the influence of thickness of different sections on the basic frequencies  $\omega_b$  and  $\omega_t$  are not the same, while  $t_1$  is the max. Therefore, regulating the thickness nearby the top is beneficial to the adjustment of the natural frequencies  $\omega_b$  and  $\omega_t$ .

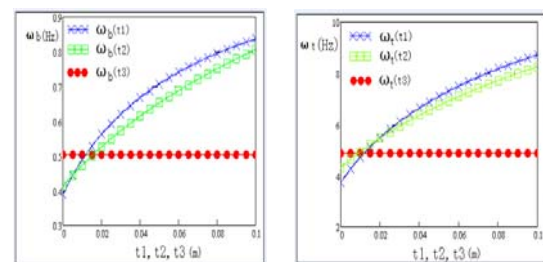


FIG.4 INFLUENCE OF THICKNESS ( $t_1, t_2, t_3$ ) ON THE BASIC FREQUENCY  $\Omega_b$  AND  $\Omega_t$

The influence of nacelle mass (M) on the natural frequencies  $\omega_b$  and  $\omega_t$  has been illustrated in Figure 5, in which the natural frequencies  $\omega_b$  and  $\omega_t$  are decreased with the increasing nacelle mass.

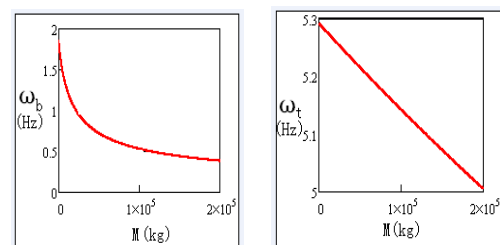


FIG.5 INFLUENCE OF NACELLE MASS (M) ON THE BASIC FREQUENCY  $\Omega_b$  AND  $\Omega_t$

In addition, the similar relationships between moment of inertia  $J_{NB}$ , offset of mass  $\Delta l$  and the natural frequencies  $\omega_t$  can be easily obtained from the formula (4).

## Natural Characteristic Research on Tower with FEM

### Finite Element Analysis Modal

In order to validate the reliability of above modal, FEA modal was created using the same parameters in ANSYS12.0. The moment of inertia is set separately along three directions, and mass node and nodes at the

top of tower are connected with rigid region. The flanges, attachment structures in tower, weld defect, residual stress etc are exxclusive from consideration. All nodes in the bottom of the modal have been fixed with full degrees of freedom. The FEA modal and constraints are shown in Figure 6.

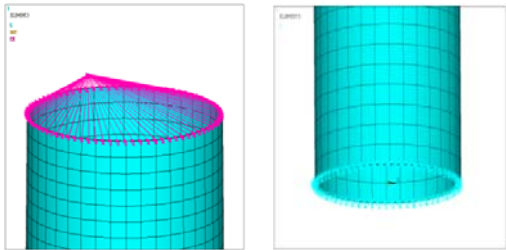


FIG.6 THE FEA MODAL AND CONSTRAINS

FEA Results

The results of comparison of the lower step natural frequencies with FEM and Rayleigh method have been tabulated in Table 1, and the corresponding mode shapes are illustrated in Figure 7. As shown in Table 1, the 1st step frequency is almost the same as the 2st order frequency because of the structure’s symmetry. Thus, the 1st and the 2st bending frequencies are combined as the first synthetical bending frequency, and the same as the 3st and the 4st. The contrasted dates indicate that the difference between the results of FEA and Rayleigh method is insignificant. Therefore the Rayleigh method is acceptable to research natural

character research of wind turbine tower.

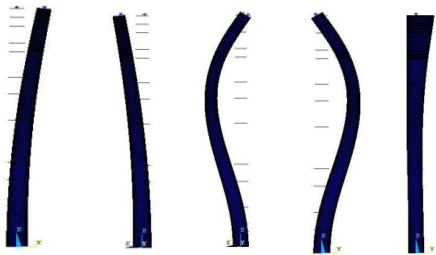


FIG.7 FIVE LOWER STEP MODE SHAPES OF TOWER

Influence of the Door on the Natural Characteristic of Tower

The influence of the door on the natural characteristic of tower is not considered in Rayleigh method. A FEA model containing the door frame is created, and the grid density near the door is reinforced. The influence of dimension and position of the door on the natural frequencies of tower is investigated. The results for different calculation schemes are shown in Table 2. Height is the distance from bottom to the centre of door; while width is the frame distance along height.

As shown in Table 2, the lower order frequencies of the model with door are no better than that of the model without door. So the influence of dimension and position of the door on the lower order natural frequencies is very insignificant and can be neglected.

TABLE 1 RESULTS COMPARISON OF THE LOWER STEP NATURAL FREQUENCIES WITH FEM AND RAYLEIGH METHOD

| FEA   |                      |                                 | Rayleigh method                                  |          | Error  |
|-------|----------------------|---------------------------------|--------------------------------------------------|----------|--------|
| Order | Natural frequency/Hz | Description of mode shapes      | The basic bending frequency by Rayleigh method   | 0.529 Hz | 13.68% |
| 1     | 0.46534              | 1st bending mode in Y direction |                                                  |          |        |
| 2     | 0.46537              | 1st bending mode in X direction |                                                  |          |        |
| 3     | 3.5547               | 2st bending mode in X direction | The basic torsional frequency by Rayleigh method | 5.142 Hz | 8.64%  |
| 4     | 3.5571               | 2st bending mode in Y direction |                                                  |          |        |
| 5     | 5.6285               | 1st torsional mode              |                                                  |          |        |

TABLE2 INFLUENCE OF THE DOOR ON THE LOWER ORDER NATURAL FREQUENCIES (HZ) OF TOWER

| Calculation schemes             |              | 1st order | 2st order | 3st order | 4st order | 5st order |
|---------------------------------|--------------|-----------|-----------|-----------|-----------|-----------|
| Calculation scheme without door |              | 0.46534   | 0.46537   | 3.5547    | 3.5571    | 5.6285    |
| Height =1.8m                    | Width =0.4m  | 0.46262   | 0.46294   | 3.5409    | 3.5419    | 5.6707    |
|                                 | Width =0.7m  | 0.46265   | 0.46293   | 3.5377    | 3.5439    | 5.6642    |
|                                 | Width =1.0m  | 0.46273   | 0.46278   | 3.5392    | 3.5399    | 5.6611    |
| Width =0.7m                     | Height =1.0m | 0.46281   | 0.46293   | 3.5401    | 3.5429    | 5.6978    |
|                                 | Height =1.8m | 0.46265   | 0.46293   | 3.5377    | 3.5439    | 5.6642    |
|                                 | Height =2.8m | 0.46268   | 0.46278   | 3.5389    | 3.5415    | 5.6801    |

## Conclusions

Adjustment on diameter, taper angle and thickness can change the natural frequency of tower, which leads to much more practical significance.

The door at the bottom has very limited influence on the natural characteristic of tower, and the influence of dimension and position of the door on the 1<sup>st</sup> natural characteristic of tower can be neglected.

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